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CHIRAL SYMMETRY OF HEAVY-LIGHT-QUARK HADRONS IN HOT/DENSE MATTER *

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The recent discoveries by the BaBar and CLEO II collaborations on the splitting between D_s and $\tilde{D}_s$ which exhibited surprises in the structure of heavy-light-quark systems are connected – via the Harada-Yamawaki "vector manifestation" of hidden local symmetry – to chiral symmetry restoration expected to take place at some critical temperature T_c in heavy-ion collisions or at some critical density n_c in the deep interior of compact stars, the main theme of this symposium. This unexpected connection exemplifies the diversity of astro-hadronic phenomena discussed in this meeting.

1. Foreword

This is the last talk of this Symposium and as such it is supposed to conclude it. What distinguishes this meeting from other meetings of a similar scope is the diversity of the topics covered, ranging from hadron/particle physics to astrophysics, but with a common objective, that is, to explore the extreme state of matter in high density or/and high temperature. Given the diversity and the exploratory stage of the development, it would be presumptuous of me to make any conclusion on any subtopic of the meeting, not to mention the totality, so what I will do is to present to you yet another surprising development that at first sight might appear unrelated to the main theme of the meeting but as it turns out, has an uncanny connection to what we have been discussing throughout this meeting.

What I shall present here is a combination of the work I did with Maciej A. Nowak and Ismail Zahed a decade ago [1] and the work I did very

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recently with Masayasu Harada and Chihiro Sasaki [2]. The question I will
address here is: *Do the recent discoveries on the structure of heavy-light-
quark mesons by the BaBar, CLEO and Belle collaborations that we have
just heard have any ramifications on what we have been discussing in this
meeting, i.e., the structure of compact stars and the early Universe?* My an-
swer is: *Yes, if the chiral phase transition predicted in QCD has significant
influence on them.*

2. The BaBar, CLEO and Belle Discoveries

On April 12th 2003, the BaBar collaboration announced a narrow peak
of mass 2.317GeV $/c^2$ that decays into $D_s^+\pi^0$ [3]. On May 12th 2003, the
CLEO II collaboration confirmed the BaBar result, and also observed a
second narrow peak of mass 2.46 GeV/c^2 in the final $D_s^{*+}\pi^0$ state [4]. Sub-
sequently both states were confirmed by the Belle collaboration [5]. The ex-
perimental results were surprising since such states were expected neither to
lie below DK and D^*K thresholds nor to be so narrow. These observations
have recently generated a flurry of theoretical activities. The excitement
surrounding these developments was nicely summarized by Nowak [6].

Remarkably, however, the existence of this type of states was theoret-
ically predicted more than a decade ago [1,7] based on the combination of
chiral symmetry of light quarks and heavy-quark symmetry of heavy quarks.
What is relevant in my discussion in this meeting is the suggestion made
in [8] that the splitting of the chiral doublers carries a direct information on
the light-quark condensate $\langle\bar{q}q\rangle$ and can therefore be a litmus indicator for
chiral symmetry property of the medium in which the chiral doubling phe-
nomenon is observed. In particular, if one measures the splitting in hot or
dense matter, then as the chiral phase transition point generically denoted
$[pt]_\chi$ (such as the critical temperature T_c or density n_c) is approached, the
splitting should disappear in the chiral limit. This could then be an ideal
tool to map out the chiral phase structure of hot/dense matter.

3. Chiral Doubling Starting From the "Vector Manifestation (VM)"

The standard approach to hot/dense-matter physics starts with a La-
grangian for cold/dilute matter for which one has both experimental and
theoretical control and then drives the system to a hot/dense environment
so as to bring it to a phase transition. This is what is being done in heavy-
ion collisions and in compact-star physics heard in this meeting. This was

the idea proposed by Nowak, Rho and Zahed in [8] for heavy-light mesons in medium. The idea of Harada, Sasaki and myself [2] is to go in the opposite direction: Instead of going from zero temperature/density to high temperature/density, that is, "bottom-up", we will go "top-down". This is because we think we have a theory which is well-defined at the critical point $[pt]_\chi$ although whether that theory is directly related to QCD is yet to be verified. Our task then is to simply assume that this description of $[pt]_\chi$ has something to do with that of QCD and then deduce the chiral doubling of heavy-light hadrons. This strategy seems to work amazingly well, giving credence to the notion of the "vector manifestation (VM)" of chiral symmetry at chiral restoration introduced by Harada and Yamawaki [9].

3.1. *The Vector Manifestation of Hidden Local Symmetry*

To make the discussion as simple as possible, I shall take in the light-quark sector all the current quark masses to be zero, the so-called chiral limit. The experiments that brought surprises involve the strange quark whose current quark mass is comparable to the strong interaction scale, namely, the pion decay constant $F_\pi \sim 93$ MeV, so to make a quantitative comparison with experiments, one would have to worry about the explicit breaking of chiral symmetry. However I believe that the qualitative feature can be captured in the chiral limit.

Now up to the transition point $[pt]_\chi$, that is, in the chiral symmetry broken phase, the relevant degrees of freedom are hadrons. In the standard way of doing things, one assumes that the only relevant degrees of freedom are the pions with other degrees of freedom such as vector mesons, baryons etc. considered to be too heavy to be relevant to the chiral phase transition. This is the picture typically given by the linear sigma model. The key point in my discussion which departs from the conventional picture is that not just the pions but also the vector mesons, namely, the ρ mesons, are quite relevant. Now how does one "see" this? One cannot see it if one has a Lagrangian with the pions and massive vector mesons coupled in the usual way which is consistent with the global symmetry but not local gauge invariant because of the vector-meson mass. With such a Lagrangian it is not easy – although not impossible – to go toward $[pt]_\chi$: There is no systematic way to compute loop corrections. In fact, there is no easy way to see whether the theory without local gauge invariance breaks down and if so, locate at what point it does so. There is however a "trick" to make the theory locate, and work up to, the break-down point. That

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is to introduce hidden local symmetry and make the theory local-gauge invariant [10]. The authors in Ref.[10] call it "fake" symmetry but it has the advantage of endowing the vector mesons with a chiral power counting [9].

To illustrate the idea, consider the chiral $G \equiv SU(3)_L \times SU(3)_R$ symmetry appropriate to three-flavor QCD. The symmetry G is spontaneously broken in the vacuum to $H \equiv SU(3)_{L+R}$, so the coordinates of the system are given by the coset space G/H parameterized by the Sugawara field $U = e^{i\pi/f}$ where π is the Nambu-Goldstone pion field. In the absence of other fields than pions, we have the well-known chiral perturbation development à la Gasser and Leutwyler. In this pion-only chiral perturbation theory, the vector mesons ρ can be introduced in consistency with the assumed symmetry. In fact there are several different ways of doing this but they are all physically equivalent, provided they are limited to tree order or the next-to-leading order in chiral perturbation. See [9] for a clear discussion on this point. The massive vectors so introduced do not, however, render themselves to a systematic chiral perturbation treatment beyond the tree order. This means that such a theory is powerless as one moves toward the $[pt]_\chi$ point. In my opinion, works purporting to describe chiral properties of hot/dense matter away from the vacuum without resorting to this strategy all suffer from this defect and cannot be trusted. This difficulty is beautifully circumvented if the nonlinearly realized chiral symmetry G/H is gauged to linear $G_{global} \times H_{local}$ as recently worked out by Harada and Yamawaki. If one fixes the gauge to unitary gauge, one then recovers the same theory without gauge invariance.

Harada and Yamawaki [9] have shown that in hidden local symmetry theory that exploits the above strategy with pions and ρ mesons as the relevant degrees of freedom and where a consistent chiral perturbation can be effectuated, the vector mesons are found to play an *essential role* at $[pt]_\chi$ since the mass of the vector meson mass goes to zero in proportion to the quark condensate $\langle \bar{q}q \rangle$. In fact by matching the HLS theory to QCD at a matching scale Λ_M above the vector meson mass, they show by one-loop renormalization-group equation involving the vector mesons as well pions that $[pt]_\chi$ corresponds to the vector manifestation (VM) fixed point at which the local gauge coupling g goes to zero and the ratio $a \equiv F_\sigma^2/F_\pi^2$ (where σ are the scalar Goldstone bosons arising from the spontaneous breaking of the gauge symmetry) goes to 1.

Up to date, there are no proofs – lattice or otherwise – for or against that the vector mass goes to zero at $[pt]_\chi$. In many conference talks (e.g., QM2004), one frequently sees view-graphs in which the ρ and a_1 masses

come together at the critical temperature T_c but at non-zero value above
the degenerate π and σ. A recent study of chemical equilibration in RHIC
experiments shows that this is most probably incorrect [11] in hot matter:
Both the $\pi - \sigma$ complex and the $\rho - a_1$ complex should become massless
at T_c. Real-time lattice calculations in temperature should ultimately be
able to validate or invalidate this scenario: The screening mass measured
on lattice in hot matter does not carry the relevant information. In the
absence of evidence either for or against it, we will simply assume that the
VM is realized at the chiral transition point and see whether the result
we obtain gives an a posteriori consistency check, if not a proof, of the
assumption.

The presence of the VM at the chiral transition point $[pt]_\chi$ implies a
scenario that is quite different from the standard one based on the linear
sigma model invoked to describe two-flavor chiral restoration. For instance,
the pion velocity at $[pt]_\chi$ is predicted to be near the velocity of light with
the vector mesons at VM [12] whereas the linear sigma model predicts it to
be zero [13].

3.2. *From the VM Fixed Point to the Nambu-Goldstone Phase*

Consider the heavy-light-quark, $Q\bar{q}$, mesons where Q is the heavy quark
and q is the light quark. Again for simplicity, I shall take the mass of Q
to be infinite – and as mentioned, that of q to be zero. Let us imagine
that we are at the VM fixed point. In constructing the Lagrangian for the
light-quark system, the relevant variables are the HLS 1-forms for the light
mesons,

$$\alpha_{R(L)\mu} = \frac{1}{i}\partial_\mu\xi_{\mathrm{R(L)}} \cdot \xi^\dagger_{[\mathrm{R(L)}]} \tag{1}$$

which transform under $SU(3)_L \times SU(3)_R$ as $\alpha_{R(L)\mu} \to R(L)\, \alpha_{R(L)\mu}[R(L)]^\dagger$
with $R(L) \in SU(3)_R(SU(3)_L)$. Since the gauge coupling g is zero at the
fixed point, the HLS gauge bosons are massless and their transverse com-
ponents decouple from the system. Two matrix valued variables $\xi_{L,R}$ are
parameterized as $\xi_{L,R} = \exp[i\phi_{L,R}]$. Here the combination $(\phi_R + \phi_L)/2$
corresponds to the longitudinal components of the vector mesons ρ (the
ρ meson and its flavor partners) in the broken phase, while the com-
bination $(\phi_R - \phi_L)/2$ corresponds to the pseudoscalar Nambu-Goldstone
bosons π (the pion and its flavor partners). With these 1-forms and since

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$a = (F_\sigma/F_\pi)^2 = 1$, the light-quark HLS at the VM takes the simple form,

$$\mathcal{L}^*_{\text{light}} = \frac{1}{2}F_\pi^2 \text{tr}[\alpha_{R\mu}\alpha_R^\mu + \alpha_{L\mu}\alpha_L^\mu], \qquad (2)$$

with the star representing the VM fixed point and F_π denoting the bare pion decay constant. The physical pion decay constant f_π vanishes at the VM fixed point by the quadratic divergence although the bare one is non-zero [9].

For the heavy mesons, one introduces the right and left fluctuation fields $\mathcal{H}_R$ and $\mathcal{H}_L$ that transform under $SU(3)_L \times SU(3)_R$ as $\mathcal{H}_{R(L)} \to \mathcal{H}_{R(L)}R^\dagger(L^\dagger)$. The fixed point Lagrangian for the heavy mesons in the presence of the light mesons takes the form

$$\mathcal{L}^*_{\text{heavy}} = -\text{tr}\left[\mathcal{H}_R iv_\mu \partial^\mu \bar{\mathcal{H}}_R\right] - \text{tr}\left[\mathcal{H}_L iv_\mu \partial^\mu \bar{\mathcal{H}}_L\right] + m_0 \text{tr}\left[\mathcal{H}_R \bar{\mathcal{H}}_R + \mathcal{H}_L \bar{\mathcal{H}}_L\right]$$
$$+ 2k\,\text{tr}\left[\mathcal{H}_R \alpha_{R\mu}\gamma^\mu \frac{1+\gamma_5}{2}\bar{\mathcal{H}}_R + \mathcal{H}_L \alpha_{L\mu}\gamma^\mu \frac{1-\gamma_5}{2}\bar{\mathcal{H}}_L\right], \qquad (3)$$

where v_μ is the velocity of the heavy meson, m_0 represents the mass generated by the interaction between heavy quark and the "pion cloud" surrounding the heavy quark, and k is a real constant to be determined.

Next we need to consider the modification to the VM Lagrangian generated by the spontaneous breaking of chiral symmetry. The gauge coupling constant becomes non-zero, $g \neq 0$, so the derivatives in the HLS 1-forms become the covariant derivatives. Then $\alpha_{L\mu}$ and $\alpha_{R\mu}$ are covariantized:

$$\partial_\mu \to D_\mu = \partial_\mu - ig\rho_\mu,$$
$$\alpha_{R\mu} \to \hat{\alpha}_{R\mu}, \quad \alpha_{L\mu} \to \hat{\alpha}_{L\mu}. \qquad (4)$$

These 1-forms transform as $\hat{\alpha}_{R(L)\mu} \to h\,\hat{\alpha}_{R(L)\mu}h^\dagger$ with $h \in [SU(3)_V]_{\text{local}}$. Apart from the kinetic-energy term $\mathcal{L}_{\rho\text{kin}} = -\frac{1}{2}\text{tr}\left[\rho_{\mu\nu}\rho^{\mu\nu}\right]$, there may be other terms, such as e.g., $(a-1)F_\pi^2 \text{tr}[\hat{\alpha}_{L\mu}\hat{\alpha}_R^\mu]$ which vanishes at the fixed point with $a = 1$. Although generally $a \neq 1$ in the broken phase, $a = 1$ gives a variety of physical quantities in good agreement with experiment in matter-free space, as shown in [9]. A detailed analysis in preparation for publication [14] shows that in the present problem, at the one-loop level that we consider, there are no $(a-1)$ corrections. Therefore we can safely set $a = 1$ in what follows. In the heavy sector, chiral-symmetry breaking will generate the term

$$\mathcal{L}_{\chi\text{SB}} = \frac{1}{2}\Delta M \,\text{tr}\left[\mathcal{H}_L \bar{\mathcal{H}}_R + \mathcal{H}_R \bar{\mathcal{H}}_L\right], \qquad (5)$$

with $\mathcal{H}_{R(L)}$ transforming under the HLS as $\mathcal{H}_{R(L)} \to \mathcal{H}_{R(L)}h^\dagger$. Here ΔM is the *bare* parameter corresponding to the mass splitting between the two multiplets and can be determined by matching the EFT with QCD.

The main finding of this approach is that ΔM comes out to be proportional to the quark condensate, i.e., $\Delta M \sim \langle \bar{q}q \rangle$.

In order to compute the mass splitting between D and $\tilde{D}$ [a], we need to go to the corresponding fields in parity eigenstate, H (odd-parity) and G (even-parity) as defined, e.g., in [8];

$$\mathcal{H}_{R,L} = \frac{1}{\sqrt{2}}\big[G \mp iH\gamma_5\big]. \qquad (6)$$

We shall denote the corresponding masses as $M_{H,G}$. They are given by

$$M_H = -m_0 - \frac{1}{2}\Delta M \ ,$$
$$M_G = -m_0 + \frac{1}{2}\Delta M \ . \qquad (7)$$

The mass splitting between G and H is therefore given by ΔM:

$$M_G - M_H = \Delta M \ . \qquad (8)$$

The next step in the calculation is to determine ΔM at the matching point in terms of QCD variables. We shall do this for the pseudoscalar and scalar correlators for $D(0^-)$ and $\tilde{D}(0^+)$, respectively. The axial-vector and vector current correlators can similarly be analyzed for $D(1^-)$ and $\tilde{D}(1^+)$. In the EFT sector, the correlators are expressed as

$$G_P(Q^2) = \frac{F_D^2 M_D^4}{M_D^2 + Q^2},$$
$$G_S(Q^2) = \frac{F_{\tilde{D}}^2 M_{\tilde{D}}^4}{M_{\tilde{D}}^2 + Q^2}, \qquad (9)$$

where F_D ($F_{\tilde{D}}$) denotes the D-meson ($\tilde{D}$-meson) decay constant and the space-like momentum $Q^2 = (M_D + \Lambda)^2$ with Λ being the matching scale. If we ignore the difference between F_D and $F_{\tilde{D}}$ which can be justified by the QCD sum rule analysis [15], then we get

$$\Delta_{SP}(Q^2) \equiv G_S(Q^2) - G_P(Q^2) \simeq \frac{3F_D^2 M_D^3}{M_D^2 + Q^2}\Delta M_D. \qquad (10)$$

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[a] Although we are referring specifically to the D mesons, our discussion generically applies to all heavy-light mesons.

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In the QCD sector, the correlators G_S and G_P are given by the operator product expansion (OPE) as [15]

$$
\begin{aligned}
G_S(Q^2) = {}& G(Q^2)\big|_{\text{pert}} \\
&+ \frac{m_H^2}{m_H^2 + Q^2}\left[-m_H\langle\bar{q}q\rangle + \frac{\alpha_s}{12\pi}\langle G^{\mu\nu}G_{\mu\nu}\rangle \right], \\
G_P(Q^2) = {}& G(Q^2)\big|_{\text{pert}} \\
&+ \frac{m_H^2}{m_H^2 + Q^2}\left[m_H\langle\bar{q}q\rangle + \frac{\alpha_s}{12\pi}\langle G^{\mu\nu}G_{\mu\nu}\rangle \right],
\end{aligned}
\tag{11}
$$

where m_H is the heavy-quark mass. To the accuracy we are aiming at, the OPE can be truncated at $\mathcal{O}(1/Q^2)$. The explicit expression for the perturbative contribution $G(Q^2)\big|_{\text{pert}}$ is available in the literature but we do not need it since it drops out in the difference. From these correlators, the Δ_{SP} becomes

$$
\Delta_{SP}(Q^2) = -\frac{2m_H^3}{m_H^2 + Q^2}\langle\bar{q}q\rangle.
\tag{12}
$$

Equating Eq. (10) to Eq. (12) and neglecting the difference $(m_H - M_D)$, we obtain the following matching condition:

$$
3F_D^2\,\Delta M_D \simeq -2\langle\bar{q}q\rangle.
\tag{13}
$$

Thus at the matching scale, the splitting is

$$
\Delta M_D \simeq -\frac{2}{3}\frac{\langle\bar{q}q\rangle}{F_D^2}.
\tag{14}
$$

As announced, the splitting is indeed proportional to the light-quark condensate. Let us denote the ΔM_D determined at the scale Λ as ΔM_{bare} which will figure in the numerical calculation.

Given the splitting ΔM_{bare} at the scale Λ, we need to decimate down to the physical scale. This amounts to making quantum corrections to the correlators written in terms of the bare quantities or more specifically to $\mathcal{L}_{\chi\text{SB}}$ in Eq. (5). This calculation turns out to be surprisingly simple for $a = 1$. For $a = 1$, ϕ_L does not mix with ϕ_R in the light sector, and hence ϕ_L couples to only $\mathcal{H}_L$ and ϕ_R to only $\mathcal{H}_R$. As a result $\mathcal{H}_{L(R)}$ cannot connect to $\mathcal{H}_{R(L)}$ by the exchange of ϕ_L or ϕ_R. Only the ρ-loop links between the fields with different chiralities as shown in Fig. 1.

This term contributes to the two-point function as

$$
\Pi_{LR}\Big|_{\text{div}} = -\frac{1}{2}\Delta M\,\mathcal{C}_2(N_f)\frac{g^2}{2\pi^2}\Big(1 - 2k - k^2\Big)\ln\Lambda,
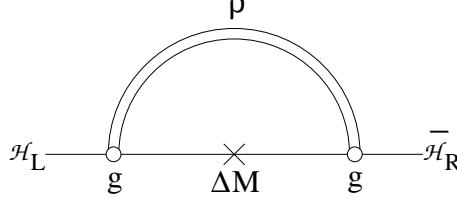\tag{15}
$$

Figure 1.   Diagram contributing to the mass difference.

where $\mathcal{C}_2(N_f)$ is the second Casimir defined by $(T_a)_{ij}(T_a)_{jl} = \mathcal{C}_2(N_f)\delta_{il}$ with i, j and l denoting the flavor indices of the light quarks. This divergence is renormalized by the bare contribution of the form $\Pi_{LR,\text{bare}} = \frac{1}{2}\Delta M_{\text{bare}}$. Thus the renormalization-group equation (RGE) takes the form

$$\mu\frac{d\,\Delta M}{d\mu} = \mathcal{C}_2(N_f)\,\frac{g^2}{2\pi^2}\Big(1 - 2k - k^2\Big)\Delta M. \qquad (16)$$

For simplicity, we may neglect the scale dependence in g and k. Then the solution to the RGE for ΔM is

$$\Delta M = \Delta M_{\text{bare}}\exp\Big[-\mathcal{C}_2(N_f)\,\frac{g^2}{2\pi^2}\Big(1 - 2k - k^2\Big)\ln\frac{\Lambda}{\mu}\Big]. \qquad (17)$$

This is our main result. This shows unequivocally that the mass splitting is dictated by the *bare* splitting ΔM_{bare} proportional to $\langle\bar{q}q\rangle$ corrected by the quantum effect given by $C_{\text{quantum}} = \exp\Big[-\mathcal{C}_2(N_f)\,\frac{g^2}{2\pi^2}\Big(1 - 2k - k^2\Big)\ln\frac{\Lambda}{\mu}\Big]$.

4. Prediction

4.1. ΔM

In the chiral limit, one can make a neat prediction on the splitting ΔM. There are no free parameters here.

I shall not attempt any error analysis and merely quote the semi-quantitative estimate arrived at in [2]. The second Casimir for three flavors is $\mathcal{C}_2(N_f = 3) = 4/3$; the constant k can be extracted from $D^* \to D\pi$ decay [16] and comes out to be $k \simeq 0.59$. By taking $\mu = m_\rho = 771\,\text{MeV}$, $\Lambda = 1.1\,\text{GeV}$ and $g = g(m_\rho) = 6.27$ determined through the Wilsonian matching [9], we find that the quantum effect increases the mass splitting by about 60%, i.e., $C_{\text{quantum}} \approx 1.6$. It turns out [14] that this result is quite stable against the matching scale Λ. Taking the value for F_D, $F_D \simeq 0.205$ GeV, and that for $\langle\bar{q}q\rangle$, $\langle\bar{q}q\rangle = -(0.243\,\text{GeV})^3$ from the literature [17] as

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typical ones, we find from (14)

$$\Delta M_{\mathrm{bare}} \simeq 0.23 \text{ GeV} \tag{18}$$

so that

$$\Delta M \simeq 0.37 \text{ GeV.} \tag{19}$$

This should be compared with the constituent quark mass $\simeq m_N/3$ where m_N is the nucleon mass. This is consist with what was observed in the experiments [3,4]. Of course, in comparing with experiments, particularly the BaBar/CLEO experiments, we need to take into account the flavor symmetry breaking which is not yet systematically investigated in the framework discussed here. But the point is that it is the quark condensate that carries the main imprint of the splitting. Another point of interest in the result is that the bare splitting depends on the heavy-meson decay constant. This suggests that the splitting may show heavy-quark flavor dependence. This could be checked with experiments once a systematic heavy-quark expansion (which is not done here) is carried out.

4.2. *Implications*

There is an obvious implication on heavy-light baryons that can be obtained as skyrmions [19,20] from the heavy-light mesonic Lagrangian. One expects off-hand that the chiral doubling splitting in heavy-light baryons would also be given by the ρ-exchange graph and hence will likewise be proportional to the light-quark condensate. Another exciting avenue would be to look at pentaquarks as skyrmions in this HLS/VM-implemented theory with a heavy quark replacing the strange quark in the recently observed Θ^+ baryon which is generating lots of activities nowadays. It would be interesting to expose the contribution to the heavy penaquark mass that bears directly on chiral symmetry as in the heavy-light mesons.

Suppose future experiments do show that in hot/dense matter, the splitting in heavy-light mesons or baryons gets reduced as temperature/density goes up in such a way as to be consistent with the vanishing splitting at the critical point in the chiral limit. An attractive interpretation of such an observation is that one is realizing the VM at $[pt]_\chi$, and hence the ρ meson mass does go to zero at the phase transition as predicted in a different context a long time ago [18]. Furthermore a recent striking development [11] on the phase structure of hot matter near T_c suggests that massive excitations in the ρ channel above T_c in the form of an instanton liquid go massless at

T_c as do the pion and the scalar σ. Lattice confirmation of this phenomenon would be highly desirable.

5. Concluding Remarks

This is a "concluding" talk in more than one sense. It is the last talk in this Symposium and is also most likely the last talk in this series of astro-hadron physics I have been helping develop in KIAS. So let me add a few of my personal remarks here.

In early 1990's, with a small group of young – as well as less young – theorists in hadronic physics in Korea I initiated a concerted effort to understand how hadronic physics involved in the strong interactions of matter can be merged into certain aspect of astrophysical phenomena that are thought to be produced under extreme conditions of temperature and/or density, a new field of research which we called "astro-hadron physics." The first international meeting in Korea bearing that name – funded by APCTP – was held at Seoul National University in 1997. With the advent of Korea Institute for Advanced Study (KIAS) originally conceived with the primary purpose of generating and developing original, innovative research activities in Korea that could be brought to the forefront of the world, the activity in astro-hadron physics was taken up at KIAS in the precise spirit of the institute's objective. With the influx of a large number of bright visitors from abroad, the activity has met with success. This then led to the first KIAS astrophysics meeting in 2000 in which astro-hadron physics figured importantly in bringing together such explosive astrophysical processes as supernovae, gamma-ray burst, black-hole formations with such explosive laboratory processes as relativistic heavy-ion collisions. The so-called hadronic phase diagram shown at this meeting was quite barren with most of the areas unexplored or empty, with little overlap between what the astronomers were observing and what the laboratory experimenters were measuring. Since then, the phase map has rapidly filled up, as we witnessed in this meeting, with measurements coming from various terrestrial laboratories (CERN, RHIC...) and from satellite observatories (Chandra, RXTE ...). This meeting is clearly a timely one to start establishing crucial connections between the two sources and synthesizing a coherent picture that will ultimately expose the structure of the novel form of matter searched for in extreme conditions of temperature and/or density.

Although this may be – at least for the time being – the last meeting of the series here at KIAS, the activity in this field should, and surely will, go

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on, if not here, then elsewhere in this country. With the advent of JPARC in Japan in tandem with that of SIS 300 at GSI in Germany together with forthcoming satellite observatories, this field is poised to develop strongly in this Asian Pacific area. It would be a pity if Korea with her early start were to miss out in this exciting new development. What I discussed in my talk together with the discovery of the novel structure in pentaquark systems promise clearly that there will be surprises and breakthroughs in store in this field.

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